Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

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LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube methods, [1] in the frequency range of approximately 500 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. [2] These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [3-10] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation.

Initial impedance tube work [2] has indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective is to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

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14. ABSTRACT

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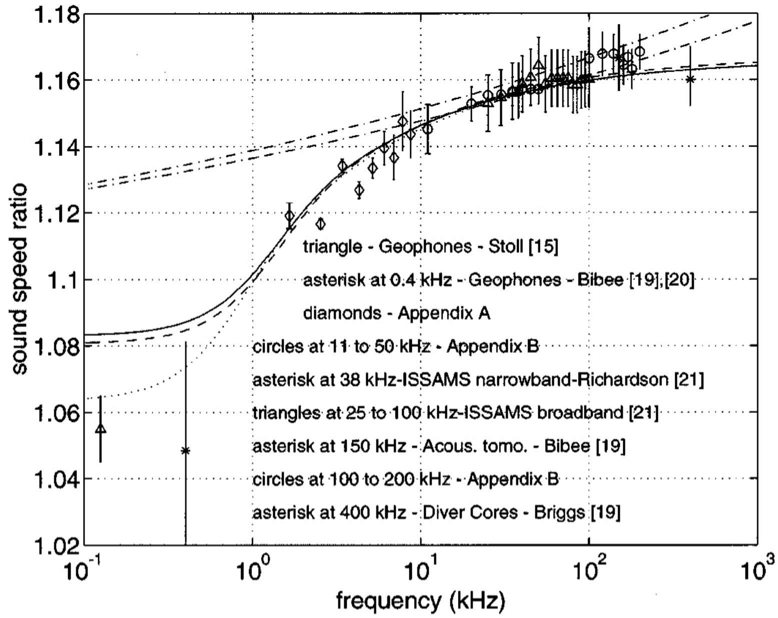

Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [26]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [26].)

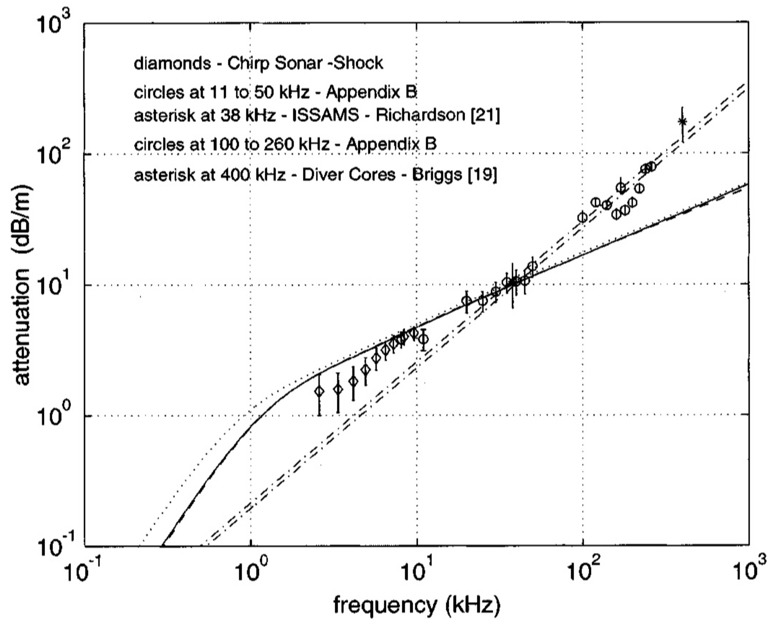

Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [26].) Also note that there is attenuation data below about 3 kHz.

APPROACH

The impedance tube technique and has been adopted as a standard technique [11-13] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [1] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [14] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It will operate in the frequency range in which dispersion is expected (about 500 Hz to 30 kHz) in typical sandy sediments. We are investigating a new impedance measurement technique [15] that does not require movement of the pressure sensor, and will minimize errors due to sensor position uncertainty. Further, we will incorporate new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling will be based on and extended from existing work for lossy fluid coupling in elastic waveguides, [16, 17] additional sample-wall boundary effects, [18] sample-fluid boundary effects [19] and asymmetric excitation. [20] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

In the final year of the project, we plan to modify the laboratory device for use on the ocean bottom for *in situ* characterization of sediments. There are two possible versions of the *in situ* device, and these were explored in an earlier study. [21] In one of the versions, the impedance tube will penetrate the ocean bottom and a reflection coefficient will be measured inside the tube. In the other version, the impedance tube will not penetrate the sediment, but will sit flush on the bottom. The impedance measurements can be made, regardless of the exact configuration and will contain information about the material properties of the ocean bottom. The interpretation of those measurements will require appropriate modeling. For example, the penetrating version could be modeled using the classic theory of Levine and Schwinger [22] for sound radiation from an open tube, in which the sediment sound speed would be a parameter. The flush-deployed version may be modeled with a finite-element numerical model such as described in [23], again with material properties as parameters. In both case, the impedance measured by the impedance tube would be compared to the appropriate model and sediment parameters varied until measured and modeled impedances are in agreement. Additional modeling beyond that described in [22] and [23] is anticipated, to obtain useful inversions for material parameters in both cases, but the raw impedance measurements themselves may prove to be useful.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Paul A. Waters is an Undergraduate Research Assistant on the project and is a UTME senior. Waters serves as an electromechanical technician and provides machine shop, procurement and software support, and oversees purchasing. Finally, Jacob G. Migliazzo is a Graduate Research Assistant, a UTME Master of Science student and contributes to all aspects of the project.

WORK COMPLETED

In the proposed course of work, the first year was devoted to design and construction of the impedance tube facility and verification of its operation via measurement of "known" materials. The facility includes the impedance tube itself, the sensors and electronics that run and monitor the experiments, and apparatus that performs supporting functions, such as water degassing and sediment preparation. Much of the primary (impedance tube) and support apparatus has been constructed. Part of the system, including the impedance tube itself is shown in Fig. 2. Some of the characteristics of the proof-of-concept system [2] are being reused, and it is primarily hardware related to those aspects that have been completed at this time. Within this category is the framework that supports the impedance tube, a thin-walled impedance tube (which serves as a place holder while the heavy-walled tube is being constructed), the sensor positioning system and the water degassing system. The primary acoustic sensors have been specified (B&K 8103's) and will be purchased shortly. (The manufacturer provided a sample that passed our evaluation.) A B&K charge amp, which will provide signal conditioning has also been purchased. A National Instruments data acquisition system is being specified. The sediment preparation system is partially completed. Finally, the heavy-walled impedance tube (1.8 m in length, 5 cm o.d., 2.5 cm i.d., weighing 200 pounds) was procured from a supplier. This aspect of the project was critical, and it took some time to find a supplier who could provide the tube. The concentricity of the tube, and the inner surface finish of the tube must be completed with a high degree of precision. Further, the material (304 stainless steel) and length of the tube limit the number of potential suppliers. A picture of the heavy-walled tube is shown in Fig. 3. Flange work is currently be added to the heavy-walled tube, and it will shortly be ready for installation in the apparatus.

In addition to the experimental apparatus construction, a literature review has been completed. The purpose of this review was to assemble information that will help us optimize the impedance measurement process, model sound propagation in the tube, and interpret the measurements, as discussed in the APPROACH section of this document. A number of important references [16-20] have been located and we have begun the implementation and analysis of some of those models.

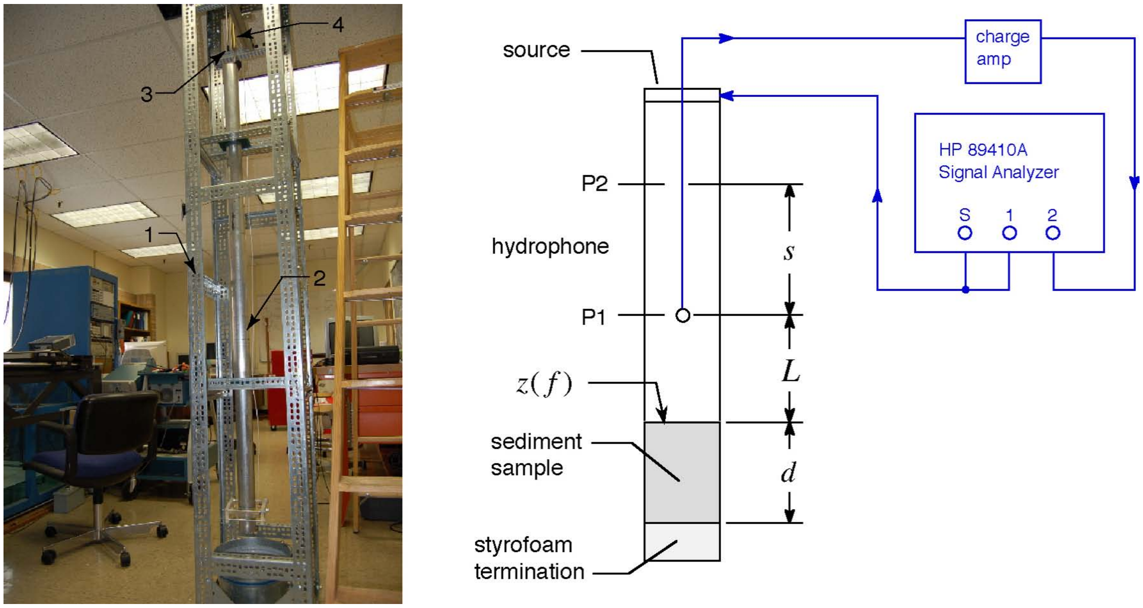

Fig. 2. On the left is shown a photograph of part of the impedance tube system in our laboratory, including the supporting framework (1), the impedance tube (2), the hydrophone (3), and the hydrophone positioning system (4). The tube in the picture is a temporary place holder for the heavy-walled tube, while it undergoes machine shop operations. On the right is a schematic diagram of the impedance tube system.

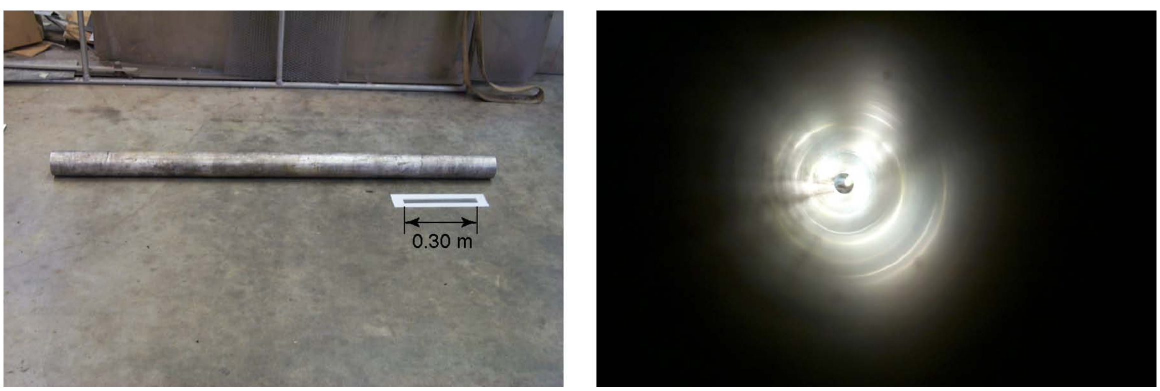

Fig. 3. On the left is shown a photograph of the heavy-walled impedance tube during machine shop operations. The 0.30 m length machinist's rule indicates the size of the tube, which is 1.83 m in length. On the right, the view down the center of the tube is shown, illuminated from the far end with a flashlight, after gun drilling and honing. Note the smoothness of the inner tube wall.

RESULTS

We are 7 months into this project, and most of the work has been devoted to developing the proposed experimental apparatus. We have also implemented some additional models of sound propagation within elastic-walled waveguides, the purpose being to allow for more advanced interpretation of the measured data, and to more fully quantify experimental error. Since the experiment is not yet ready to run, we do not have any new measurements, but we have applied some of the new modeling to an existing data set, and generated some new results, described below.

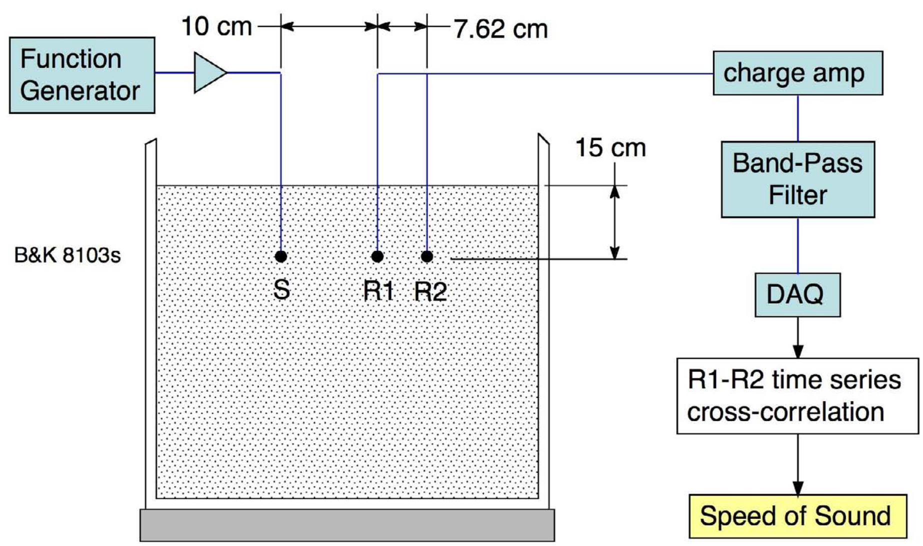

Fig. 4. A schematic diagram of the time-of-flight experiment is shown. A large thin-walled cylindrical container was filled with 60°C degassed water and sorted and washed medium grain blasting sand. Three B&K 8103 hydrophones were placed in the sediment and time-of-flight measurements were obtained after cooling. A function generator and power amplifier were used to drive one of the 8103s as a source. The remaining two 8103s were used as receivers. Their signals were conditioned with a charge amp and a band-pass filter. The voltage signals were acquired with a digital oscilloscope and cross correlated to extract the time-of-flight. Sound speed was then calculated from the 7.62 cm sensor separation distance.

Measurements of the sound speed of an artificial water-saturated, sandy-sediment contained within a thin-walled cylindrical tank were obtained by the author and co-workers in a previous study. [24] Schematic diagrams of the experimental apparatus and procedure are shown in Figs. 4 & 5. Above 20 kHz, the sediment sound speed was measured directly using time-of-flight. Below 20 kHz, the frequency-dependent sound speed was inferred from the measured resonance frequencies of the system by initially approximating the thin-walled cylinder as pressure-release. Both symmetric and asymmetric modes of the system were excited. An elastic waveguide model for symmetric modes was then used to infer the free-field sediment sound speed from that measured within the tank, for the *symmetric modes only*. Our current effort has resulted in a model for *asymmetric* modes, and has allowed us to analyze the remaining data from Ref. [24]. The sound speed dispersion for the sandy sediment is shown in Fig. 6. This dispersion is fairly well-described by Williams' Effective Density

Fluid Model [EDFM], without any fitting of the material input parameters. [10] We do observe speeds that are slightly lower than the EDFM prediction, though. We also observe about a 2 % variation in the sound speed at different locations within the sediment, even though the sediment is composed entirely of one type of sand, with no shell or rock fragments, and appears to be homogeneous.

The significance of this result is the following: There is very little experimental sound speed data from well-controlled and well-characterized sandy sediments in the frequency range in which dispersion is expected to appear (below about 10 kHz). This new data represents one of the only experiments in which both high and low frequency sound speed measurements have been obtained within the same volume of sediment. With the experimental errors well-characterized, we can confidently conclude that dispersion is present, and that it is closely modeled by the EDFM, yet, there is some over-prediction at the lower frequencies. This adds to a small, but growing collection of data in support of a Biot-based model for sound propagation in sandy marine sediments. It also adds to a small collection of data that is over predicted by current Biot-based models.

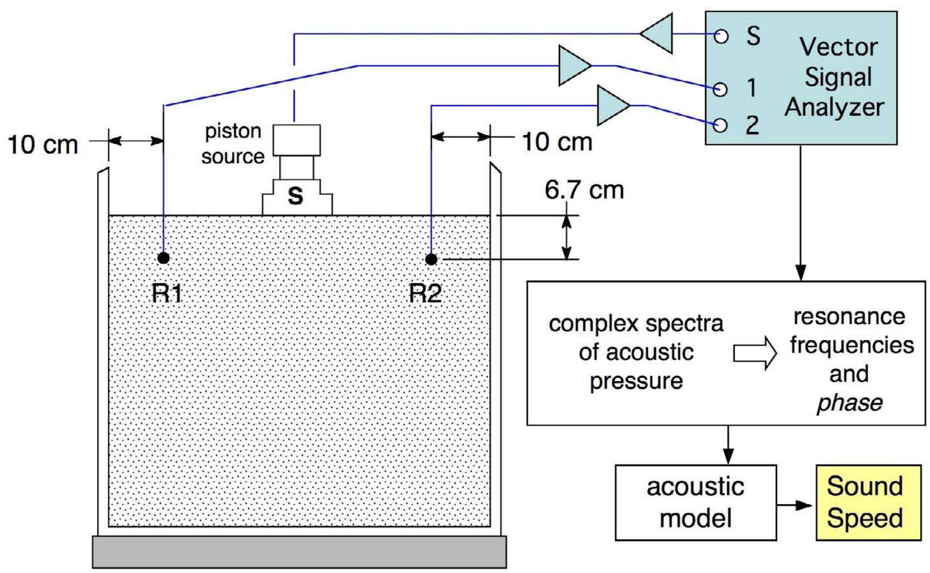

Fig. 5. A schematic diagram of the resonance experiment is shown. A constant-velocity tonpiltz source was used to excite the system. By placing it in the center, symmetric modes were excited. By placing the source midway between the center and the wall, asymmetric modes were excited. The source was driven with periodic chirps and the pressure spectra were recorded at positions R1 and R2. Analysis of the spectra yielded resonance frequencies which were in turn related to the frequency-dependent sound speed of the sediment. The effect of the finite impedance of the tank walls was accounted for, and found to be small.

Another conclusion one might draw, although with less confidence, is that residual gas may contribute to this over prediction, and that residual gas is difficult (if not impossible) to remove from sediment particles that have been exposed to gas. Finally, these results underscore the statistical nature of sound propagation in a granular material, and indicate that even for a sediment composed of “homogeneous” granular material, one will encounter variation in the acoustic properties. These new results, the data analysis and experimental description are reported in [25]. Our current experimental work seeks to add to this data, but for a wider range of frequencies, including attenuation, and with greater accuracy.

IMPACT/APPLICATIONS

The Biot-based description of sound propagation within sandy marine sediments is gaining support in the ocean acoustics and related research communities, but we are also coming to the conclusion that it not fully adequate. More research is needed and is certainly underway to increase our understanding of sound propagation in the ocean bottom. As this process progresses, one application will be to update the models used in operational sonar systems. A better description of bottom interaction will increase our ability to detected, localize and classify targets in littoral environments. The same can be said for buried objects.

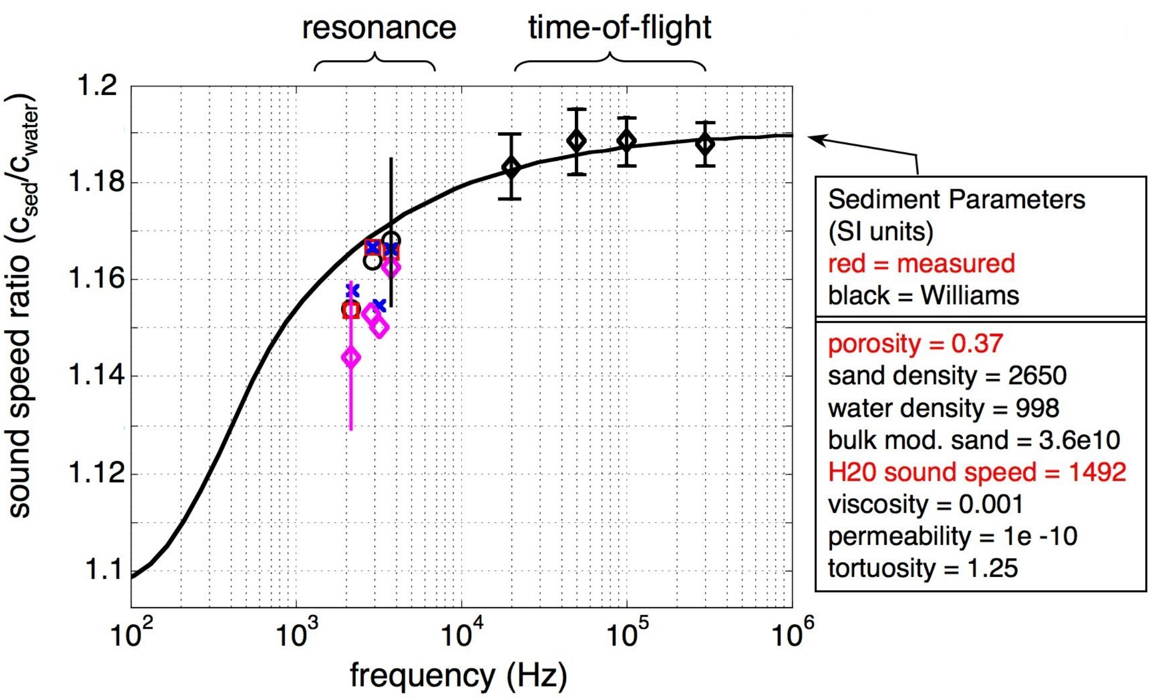

Fig. 6. Normalized sound speed measurements, the result of new analysis, are compared to the EDFM (solid line). Black circles and red squares were obtained at two different sediment locations, with the sound source in center, and hence were inferred from the resonance frequencies of axisymmetric modes. Blue x's and magenta diamonds were obtained at the same two sediment locations, but with the sound source located off-center, and hence were inferred from the resonance frequencies of asymmetric modes. Black diamonds are from the time-of-flight measurements. Error bars represent length and time uncertanties, but due to the close grouping of some of the data, they are not shown for every data point. The material parameters (in pure SI units) required for evaluation of the EDFM are shown in the table to the left of the plot. The values shown in red were measured and specifically refer to the sediment in this study. The values shown in black were taken from Ref. [10], for a similar type of sand. No adjustment of material parameters was conducted, nor was any fitting performed. The EDFM agrees very well with the time-of-flight measurements, within the range of measurement uncertainty in each case. The upper third of the resonance-based measurements are in agreement with the EDFM, but the degree of agreement diminishes as frequency continues down. For the lowest few frequencies, the data points and the upper limit of the error bars are over-predicted by the EDFM.

RELATED PROJECTS

SAX99: Sediment Acoustics Experiment 1999
From the project web page: SAX99 addresses high-frequency sound penetration into, propagation within, and scattering from the shallow-water seafloor at a basic research (6.1) level.
http://www.apl.washington.edu/programs/SAX99/Program/prog.html

SAX04: Sediment Acoustics Experiment 2004
From the project web page: The overall objective of SAX04 is to better understand the acoustic detection at low grazing angles of objects, such as mines, buried in sandy marine sediments. One component of the SAX04 work is designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. A second component is designed to provide data directly on acoustic detections of buried mine-like objects at low grazing angles.
http://www.apl.washington.edu/projects/SAX04/summary.html

Other ARL:UT sediment researchers: Marcia Isakson and Nicholas Chotiros both conduct research on sound propagation in marine sediments.

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P.S. Wilson and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," in *Proceedings of the IEEE Oceans '05 Europe Conference*, Brest, France, June 20-23, 2005. [refereed, in press]

P.S. Wilson and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," *IEEE Journal of Oceanic Engineering*, 2005. [refereed]